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TURBINE TEST RESULTS**

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IMPROVED PFB OPERATIONS: 400-HOUR TURBINE TEST RESULTS

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INTRODUCTION

An advanced concept under development for the production of electric power from coal involves pressurized fluidized bed coal technology. In this concept granular coal is burned in the presence of granular limestone or dolomite. This technology permits the burning of coals with a wide range of chemical compositions, including those high in sulfur, while providing adequate environmental control. Another attraction of the pressurized fluidized bed (PFB) technology issues from the possibility of efficiently generating electric power both from steam and from the operation of a gas turbine directly in the combustion effluent. However, early experience with turbines operated in similar environments showed that turbine performance was seriously impaired by erosion and corrosion of airfoil surfaces or by fouling (refs. 1 to 6). To determine if this concept offers useful turbine lifetimes, it is essential that damage mechanisms be identified and located with respect to airfoil surface positions.

In the first phase of the Lewis Research Center PFB turbine material project, wedge-shaped turbine material specimens showed extensive erosion and corrosion damage when rotated directly in the effluent from the PFB combustor (ref. 7). Such damage was not unexpected however, since in these tests no provisions were made for cleanup of the limestone and coal ash in the combustion gas. In the next phase of the turbine materials project, a small, single-stage turbine was installed. A two-stage cyclone particle separator in the gas transport system between the combustor and the turbine reduced gas particulate loading. Three turbine runs were reported at gas and rotor velocities comparable to utility turbine operating conditions (ref. 8). The gas loadings were moderate to high (560 to 2800 ppm; 0.3 to 1.5 grains/std ft³) for the several coal/sorbent combinations used in these tests. Heavy erosion and accelerated oxidation occurred on blade surfaces in all three tests.

Recent improvements in PFB operations resulted in more stable operating conditions and lower solids loadings. Improvement of the collection efficiency of the cyclone particle separator reduced the loading in the combustion gases and made possible a 400-hr turbine test. The

results of this test permit a more reliable projection of life limiting mechanisms applicable to superalloy utility turbines operating in PFB effluents and are reported in this paper.

COMBUSTION PARAMETERS AND OPERATING PROCEDURE

A cutaway view of the PFB test cell is shown in figure 1, and a detailed schematic of the PFB combustion and turbine test systems is shown in figure 2. The combustor (reactor) is about 300 cm (10 ft) high and conical in shape with top and bottom diameters of 47 and 23 cm (19 and 9 in.), respectively. Coal and sorbent materials are stored in hoppers within the test cell and are metered into the reactor. The reactor combustion gases flow through a cleanup system above the reactor before entering the test turbine on the building's top floor. A control room and shop are adjacent to the test cell.

Instrumentation of the facility was designed to measure about 200 different test variables, including temperatures, pressures, mass flows, and system weight changes (refs. 9, 10). A gas analyzer was connected to the combustor gas exit by means of a steam-jacketed sampling line to determine quantities of sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO₂), carbon monoxide (CO), hydrocarbons, and oxygen (O₂) in the gases. Gas composition analyses were, therefore, made at steam temperature. Particulate samples were collected both upstream (cyclone separator) and downstream (small cyclone separators and micropore filter) of the turbine, and the solids were subsequently analyzed for particle size and chemical composition. The computerized data collection system was also used for control monitoring and for limit violation warnings.

Combustion Operating Procedure

The PFB facility was operated 5 days per week. Initially the reactor bed was loaded with about 110 kg (250 lb) of new or used bed material to bring the bed depth to about 180 cm (70 in.). Coal (Pittsburgh No. 8 or Ohio) and sorbent (Grove City limestone or dolomite) were metered and blended in about a 7:1 ratio and then loaded into a lock hopper injection system. Both coal

and limestone were screened to 7-12 mesh size (~0.25 cm; 0.1 in.). The reactor bed was preheated to 760° C (1400° F) with a natural gas and air torch located in the side of the reactor. Combustion air was slowly brought on stream, and the bed was fluidized and pressurized to about 6 atm. During combustion the air, coal, and limestone flow rates were about 292, 13.5, and 2.0 kg/hr (650, 30, 4.5 lb/hr) respectively.

The coal flow rate was continuously adjusted during the test to maintain the reactor bed temperature close to 1000° C (1850° F), and the limestone flow rate was adjusted to maintain a Ca/S mole ratio of about 2:1. Fuel flow was controlled on the lower bed temperature. The upper bed temperature increased steadily with time until it reached a value 5 to 15 C° (10 to 30 F°) cooler than the lower bed temperature after about 4 days. The combustion air flow rate into the reactor was adjusted to maintain a lean fuel to air mixture and to maintain the velocity of gases flowing through the fluidized bed surface at less than 0.6 m/sec (2 ft/sec). In previous Lewis tests (refs. 9, 10), reduction of flow velocity also reduced solids loading. Attempts were made to keep the velocity low enough so that solids loading from the reactor would be less than 3700 ppm (2 grains/std ft³), and yet to keep airflow high enough so that the design speed of the turbine could be attained.

During the startup period, the reactor exhaust gases were vented to the atmosphere through a turbine bypass system. The combustion gases which passed through the cyclone solids separator were dead headed downstream of the turbine by means of a valve. When the reactor exhaust gases reached the desired temperature and pressure, the bypass system was slowly closed as the turbine valve line was opened to permit combustion gases to flow through the turbine. Because of heat losses in the piping, gases entered the cyclone separator 30 to 50 C° (50 to 100 F°) cooler than the top of the fluidized bed, and the drop through the separator was about 50 C° (100 F°). The total temperature drop from reactor to cyclone separator exit was therefore 75 to 100 C° (150 to 200 F°). The gases leaving the turbine flowed through a water cooling system before entering the downstream solids separators. Before exiting through the backpressure control valve, the warm air flowed through a heat exchanger that preheated the incoming combustion air to 38° C (100° F).

Over a five week period, 400 hours of test time were accumulated on the PFB system and test turbine. Table I shows the average values of combustion test parameters for each of the five weeks. Test conditions remained relatively constant at targeted values set on the basis of previous experiments.

System Improvements

The achievement of stable combustion conditions and low solids emission levels permitted

the 400-hr turbine test and were the direct result of several key system improvements made before and during the test. These improvements include (1) redesign of the air feed system to the combustor to reduce plugging and channeling, (2) removal of the heat exchangers in the bed to permit adiabatic operation, and (3) redesign of the cyclone separator. The third factor was especially important in reducing solids loading levels. Other operating conditions were adjusted to maintain a gas temperature of about 770° C (1420° F) at the turbine as well as adequate pressure and mass flow to operate the turbine.

During the first week of testing, separator efficiency was very poor, and gases sometimes contained more than 1870 ppm (1 grain/std ft³) of solids in individual samples collected downstream of the turbine (table II). As originally purchased, the separator design incorporated a parallel pathway for the gases to flow through the unit (fig. 3). The combustion gases were introduced into the two-stage unit tangentially on the side. The gases were then split, one part swirling upward through the first stage, and the other part swirling downward through the second stage. The gases combined within the second stage and then flowed out of the entire unit through a single exit pipe. In this configuration, only about one-third of the gas followed the long swirl path through both stages, and only one out of four particles fell to the bottom of the stages to be discharged. The remainder flowed through the turbine.

The separator was modified so that all the gases traversed the first stage and entered the swirler at the top of the second stage. The exit pipe was extended deeper inside the second stage, thus causing the gases to swirl much further downward before they could change direction and exit the unit. This separator modification increased the gas pressure drop through the unit, but it also increased solids removal efficiency from 25-50 percent to 90-99 percent. Additional cyclone improvements included adding heavier insulation at key areas to minimize heat loss, and packing of internal separator joints to prevent cracking from thermal expansion.

Gas and Solids Analysis

The average composition and particulate loading of gas flowing from the separator and into the turbine (on a weekly basis) are shown in table II. The oxygen content in the gases during all test weeks, was 11 to 13 volume percent, reflecting the fuel-lean operating conditions. Carbon monoxide and hydrocarbon concentrations were generally less than 10 ppm. The nitrogen oxides in the gas ranged between 200 and 300 ppm, generally less than the pollution limit of 0.7 lb/million Btu. The average sulfur oxide concentration was about 300 ppm, with maximum values of 350 ppm during the middle phase of testing and about 250 ppm during the last phases of testing. The SO_x and NO_x concentrations appeared to increase and decrease proportionately. Only at

maximum concentrations did the SO_x emissions exceed the Federal pollution limit of 1.2 lb/million Btu. Figure 4 shows the variation with time of gas temperature and pollutants during the entire test run.

The solids loading of gases from the bed (into the cyclone) averaged 2800 ppm (1.5 grains/std ft³), and ranged from 1870 ppm (1 grain/std ft³) to slightly over 3740 ppm (2 grains/std ft³) (table I). Solids samples were taken over 3 to 8-hour increments for a total of about 65 samples. Total solids were determined by taking the sum of solids collected at the cyclone separator and solids collected downstream of the turbine. The gases flowing through the separator emerged at about 800° to 900° C (1500° to 1600° F) and 5 atm pressure, and contained 20 to 200 ppm (0.01 to 0.10 grain/std ft³) of solids during most of the test time (table II). Cyclone efficiency ranged from 90 to 99 percent.

The particle size distribution of solids which passed through the turbine was determined by the Coulter method. Sieving to 100 μm removed debris (>500 μm) which was most likely associated with scale from pipe downstream of the turbine and larger "particles" (100 to 500 μm) which may have agglomerated in the presence of moisture after capture by the separators. Scanning electron micrograph (SEM) examination of particles in the 100 to 200 μm range reflects this compaction of smaller particles (fig. 5). Coulter analyses of the size distribution of particles less than 100 μm in diameter at several loading levels for several weeks during the test are shown in figure 6. The Coulter analysis was performed with a 280 μm aperture tube, and particles less than 4 μm in diameter were therefore not counted. (These small particles pass through the aperture but are not sensed by the electronic system, which is tuned to larger particle sizes.) Particles below 4 μm probably comprise no more than 10 percent of the sample. On the basis of the Coulter analysis, 70 to 80 percent of the particles less than 100 μm in diameter are less than 20 μm as compared with 55 to 80 percent in previous tests. The average particle size was approximately 15 μm .

The color of the solids samples ranged from light brown to rose, indicating variations in composition over the test period. X-ray and chemical analyses of typical solids samples are shown in table III. From sample to sample, the range of solid components detected by chemical analysis varied from 25 to 50 percent, but the average chemical composition of both solids collected by the separator and those passing through the turbine reflects the composition of the coal ash. In general the most dominant X-ray patterns are associated with SiO_2 , Fe_2O_3 , and CaSO_4 or hydrated CaSO_4 , but these compounds represent a very small percentage of the total sample. The low X-ray concentrations of SiO_2 and Fe_2O_3 suggest the presence of more complex silicon and iron compounds, such as Al-Si compounds and various clays present in coal.

Mullite has been detected, as well as some X-ray lines which may be associated with anorthites.

The quantity of calcium in both the separator and turbine solids was reported as CaO in the chemical analysis. So that the amount of CaSO_4 could be determined from chemical analysis, all the sulfur was assumed to be present in the form of CaSO_4 (footnote b, table III), and the remainder of the calcium was then assumed to be present as CaO . The calculated and X-ray values of CaSO_4 agree closely in the separator solids samples, but the calculated value appears to be too high in the turbine samples. This discrepancy between the calculated CaSO_4 value and the X-ray value in turbine solids may indicate that some sulfur is tied up in other species, such as alkali-metal sulfates (Na_2SO_4) and alkali-metal-iron trisulfates ($\text{K}_3\text{Fe}(\text{SO}_4)_3$). (Sodium and potassium concentrations were also higher in solids that passed through the turbine.) These sulfur-bearing species may have formed on the surface of particles during the passage of gas and solids from hotter to cooler regions in the flow path. Solids that pass through the turbine form the adherent rose-colored deposit that was seen on blades of the test turbines.

TURBINE SYSTEM

Turbine Test Unit

The turbine used in this research was a modified Chrysler baseline automotive unit from the NASA Chrysler Automobile Project. The integrally bladed turbine (IBT) was designed to operate at a mass flow 12 to 15 times greater than that generated by the NASA Lewis PFB coal combustor (300 kg/hr; 650 lb/hr). To accommodate the low flow capacity of the combustor and to generate rotor tip speeds comparable to those of utility turbines (~300 m/sec; 1000 ft/sec), the turbine was operated at 6 percent partial admission. Therefore, 3 blades of a total of 53 were directly exposed to the high-velocity PFB effluent gas stream at any given time. At the test speed of 40,000 revolutions per minute and with a pressure ratio of 1.95, the turbine generated 5 to 8 horsepower with partial admission.

An isometric sectional drawing of the single-stage turbine is shown in figure 7. The turbine assembly contains turbine components in two subunits - the front and rear housings. The front housing consists of two Hastelloy flanges that form the cavity in which the rotor turns. The hot combustion gas enters the turbine through the single stator passage, expands in the rotor cavity, causing the rotor to turn, and exits the turbine through the flange opening shown in the figure. Two inspection ports permit visual examination of the rotor's leading and trailing edges during test downtime.

During turbine operation, pressure in the front housing is about 5 atmospheres while pressure in the rear housing is near 1 atmosphere.

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This pressure difference is maintained by means of a double carbon seal assembly that is press-fitted into the narrow region between the front and rear turbine housings. The two carbon ring seals just behind the turbine rotor fit snugly around the turbine shaft. A small high-pressure air purge between the carbon seals ensures the pressure integrity in each housing.

The turbine journal and thrust bearings are lubricated and cooled by the circulation of oil from a water-cooled oil reservoir. Temperatures of bearings and oil are monitored by thermocouples which are incorporated into the automatic warning and turbine shutdown system. A dual-purpose air-starter/brake assembly is attached to the rear end of the rotor shaft. The air brake, which is operated by compressed air, regulates the rotational speed of the rotor.

To monitor turbine performance, the following sensors were mounted in the rear turbine housing along the turbine shaft - two proximity probes, two accelerometers, and three magnetic speed pickups. The proximity probes, one horizontal and the other vertical, were mounted 0.13 mm (0.005 in.) from the rotor shaft. The outputs of these probes were fed into an oscilloscope and produced an "orbit" on the screen. The size of the orbit and its position on the screen indicated whether the shaft was rotating true. Accelerometers or vibration sensors are solid-state devices used to indicate any roughness in the rotation of the rotor. The accelerometer outputs lead to an amplifier located in the control room. The amplifier has relay contacts which, if excited by a jolt such as the loss of a blade, will give an alarm and initiate turbine shutdown. Three magnetic speed pickups were positioned 0.20 mm (0.008 in.) from a six-toothed wheel which was attached to the end of the rotor shaft. The outputs of these devices indicated the number of rotor revolutions by responding to the number of teeth that rotated past them in a given time.

Pressure taps were located on the gas inlet tube wall, at the stator exit near the rotor tip, and in the rotor exit port. Turbine pressure ratio was regulated by adjusting the backpressure control valve to vary rotor exit pressure. Thermocouples located in the turbine housing indicated combustion gas inlet and exit temperatures.

Turbine Rotor

The integrally cast superalloy turbine rotors contained 53 blades on a 15-cm (6-in.) disk. The rotors were cast with arc slots beneath the blade platform. The purpose of this slotting was to contain any cracks that might issue from the blade platform during operation and thus prevent their propagation to the rotor hub. Shafts of 8640 steel were friction welded to the prepared rotor stubs. After rough machining, the friction-weld area was examined for integrity. If the weld proved sound, the steel

shaft was machined to final dimensions. Before installation, three blades in each quadrant of rotor were measured at each of 12 surface positions and three lengths for reference after test exposure. The finished turbine rotor, with rotating components on the shaft, was spin balanced before it was installed in the turbine housing.

TURBINE TEST OPERATING PROCEDURES

During the preheat phase, which usually took 6 to 8 hr, the turbine was turned by means of the air-starter/brake assembly at a slow speed (500 to 1500 rpm). The slow rotation of the rotor prevented preferential buildup of deposit on exposed blades before testing. When the bed and combustion gas temperatures reached the desired level, hot combustion gases were permitted to flow through the turbine. The turbine rotor gradually increased speed until it was rotating at test speed. This required about an hour. The gas temperature at the rotor inlet gradually increased to 700° to 800° C (1300° to 1500° F) over a 3- to 12-hr period, during which time the pressure ratio and gas velocity through the turbine were maintained at the desired level. Temperature and pressure conditions were steady after the initial startup. In previous tests where solids loadings were high, the turbine eroded severely within 12 hr. During the 400-hr test the turbine was rotated at a moderate speed (15 000 rpm) until the solids loading level could be established and maintained below 200 ppm (0.1 grain/std ft³). During shutdown the gases were diverted back through the turbine bypass line, and the rotor was allowed to cool gradually while rotating again at 500 to 1500 rpm.

Previous Turbine Tests

Previous IBT tests were run with several nickel-base alloy blades and coal/sorbent compositions. The results of three runs (R3, R4, and R5) have been reported (ref. 8). Table IV is a summary of operating conditions for turbine tests R3 through R7, and table V is a summary of erosion/corrosion results. The rotor alloy in one test was Alloy 713LC (12.5 percent Cr, 3 percent Al, 0.6 percent Ti). In the remaining tests the alloy was IN-792 + Hf (12 percent Cr, 6 percent Al, and 4.5 percent Ti). The pressure ratio across the turbine was maintained at 2:1 in tests R3 through R6, and the rotation speed was maintained at 40,000 rpm. At this rotation speed the relative gas velocity at the rotor inlet was about 300 m/sec (1000 ft/sec). The variation in erosion rate in tests R3 through R6 was a function of solids loading, gas velocity, and coal/sorbent type. Test R3 was longer because solids loadings were less than in other tests. Differences in corrosion results reflect, in turn, differences in erosion rate as well as temperature and material. The variation in solids loading through the turbine produced a wide variation of erosion/corrosion results ranging from complete loss of blades (test R4) to the successful

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400-hr test (R7). Figure 8 shows loss of the trailing edge tips of R5 blades after 12 hours.

400-Hr Test (R7)

As a result of previous test runs, Pittsburgh No. 8 coal with limestone was selected as the coal/sorbent combination that would yield the least solids carryover in the gas during test R7 and thereby diminish erosive damage to the turbine. In addition, the bed was burned adiabatically (without cooling tubes). Figure 9 shows the gas solids loading for several coal/sorbent combinations run in previous tests. The combustion solids were heaviest in the R4 test run with dolomite (7300-ppm; 3.9-grain/std ft³). This test was also run nonadiabatically. It is possible that the finer in-bed dolomite particles are efficient in reducing SO_x emission, but generate a large amount of carryover from the bed. Even in combination with limestone, Ohio coal appeared to generate a large amount of carryover when the combustor was operated nonadiabatically (test R5), and the cyclone did not operate efficiently. A return to Pittsburgh/limestone and adiabatic conditions (test R6) seemed to produce both lower bed solids carryover and more efficient cyclone operation. Further reduction in solids through the turbine in test R7 also reflects the improved cyclone efficiency after modification. During some 3 to 8-hr periods of the R7 tests, measured solids loading levels through the turbine were as low as 20 ppm (0.01 grain/std ft³).

During the first 200 hours (test R7-A) the turbine was run at low speed (~15,000 rpm) for about 30 percent of the time to keep the erosion rate down during periods of uncertain or high solids loading levels. The relative gas velocity at the rotor inlet was about 130 m/sec (400 ft/sec). The rotation speed and pressure ratio were chosen to maintain congruent turbine velocity diagrams, and thus preserve gas flow angles at 15,000 rpm similar to those at 40,000 rpm. Average solids loading during this period was about 400 ppm (0.2 grain/std ft³) (table IV), with peaks as high as 1100 ppm (0.6 grain/std ft³) prior to cyclone modification. After exposure for the first 200 hours, three blades were cut from the rotor for metallographic analysis, and erosion measurements were made on several of the previously measured blades. The rotor was then rebalanced and reinstalled in the turbine housing for further testing.

During the last 200 hours (test R7-B) solids loadings were consistently near 100 ppm (~0.05 grain/std ft³), and the turbine was run at low speed only 10 percent of the time. The rotation speed was 38,000 to 40,000 rpm 90 percent of the time. An effective erosion factor may be defined as

$$EF_1 = \frac{(v^{2.5})(\text{Solids loading})(\text{Time})}{\sum_i [(v^{2.5})(\text{Solids loading})(\text{Time})]_i}$$

for each fraction of the run, where v is velocity and i refers to the two operating relative gas velocities (130 m/sec at 15,000 rpm; 300 m/sec at 40,000 rpm). The velocity exponent is based on an earlier Lewis erosion result, and erosion dependence on solids loading is assumed to be linear in this model. If the fraction of total erosion suffered by the blade during the low- and high-velocity portions of the test is calculated by using this erosion factor, low-velocity erosion accounts for only 4 percent of the erosion loss during the first 200 hours and for 1 percent of the erosion loss during the last 200 hours. The low-velocity portion of the test was negligible from an erosion standpoint but must be included for corrosion. The total erosion time at high velocity was therefore 320 hours at partial admission, and the total corrosion time was 400 hours.

EROSION/CORROSION RESULTS

Previous Turbine Results (Tests R3 through R6)

Preliminary erosion/corrosion results obtained from the three previous IBT tests (R3, R4, and R5) shown in table V indicated that corrosion may be present on bare superalloy rotors even at severe erosion rates (0.01 to 0.33 mm/hr; 0.4 to 13 mils/hr) (ref. 8). In these studies, centrifugal separation of heavy particles produced non-uniform erosion on the surface of the blades, with erosion to bare metal primarily at the leading edge center and the trailing edge tip. The presence of accelerated oxidation or sulfidation over the remainder of the blade at sites of lighter particle bombardment suggested two possible corrosion enhancement mechanisms: (1) an erosion/corrosion enhancement which may occur when protective oxide layers are continually eroded, exposing underlying nickel-rich depletion zones that may corrode more easily; and (2) a deposition/corrosion enhancement mechanism which may occur when sulfur-rich species in the deposit react with the metal or oxide surface. Oxide and sulfide morphologies that may be associated with both these mechanisms have been seen on R3, R4, and R5 blades. The gases contain significant quantities of SO_x and may also be corrosive; however, it is unlikely that the exact P_{SO_2}/P_{O_2} composition is present at various gas pressures over the blade surface to produce the oxy-sulfides observed. The results of these tests suggested that internal oxidation, nonprotective oxides, and sulfidation might be major damage mechanisms at lower solids loadings.

Test R7-A - First 200 Hours

The erosion/corrosion results for test R7-A are shown in table V. After 200 hours, the R7-A blades exhibited deposits of bed solids about 0.05 mm (2 mils) thick. Deposit and internal oxides covered nearly the entire blade surface (fig. 10). The absolute loss in blade thickness measured at various positions on the blade surface was negligible (<0.025 mm; 1 mil), although

erosion was evident near the leading edge in SEM photographs. Metallographic examination of the three extracted blades revealed an intricate oxide penetration network (fig. 11) beneath a thin (5 μ m) surface layer of primarily aluminum and titanium oxides. Total penetration of both oxides and the depletion zone is about 20 μ m. Uniform enhanced oxidation over the blade surface suggests (1) that centrifugal particle separation was reduced in this test from the level in previous tests because isolated areas of erosion to bare metal were less prevalent and (2) that erosive removal of aluminum-rich oxides over the entire blade surface reduced the protectiveness of the oxide (refs. 11, 12). Although the formation of surface oxides may be somewhat protective against erosion, accelerated oxide penetration is itself a problem.

Test R7-B - Last 200 Hours

The appearance of the R7-B blades after 400 hours is shown in figure 12. Adherent deposits covered the suction side and occurred primarily near the leading edge on the pressure side. Some evidence of heavy particle bombardment was visible at the trailing edge tip and near the center on the pressure side. However, the trailing edge tips were still structurally sound in contrast with the R5 blade tips. The maximum surface erosion loss was 0.15 mm (6 mils) at the leading edge, and the average erosion loss over the surface was 0.025 mm (1 mil) (fig. 13). From the average surface loss rate the projected full admission erosion rate at this loading and particle velocity is about 2 mm/1000 hr (70 mils/1000 hrs).

A metallographic cross-section of an R7-B blade after 400 hours is shown in figure 14. Corrosion occurred primarily beneath the most adherent deposit, and visible erosion sites were generally sites of accelerated oxidation but not sulfidation (fig. 15). The penetration of alumina (accelerated oxidation) and one form of sulfur penetration resembled forms seen in previous Lewis turbine tests (ref. 8). This type of sulfidation, seen in R3 blades (Alloy 713LC) at lower average temperatures 704° C (1300° F), is characterized by the presence of atypical chromium-rich oxides and a uniform sulfur front (fig. 16). There appears to be no γ' depletion beneath the front. This morphology strongly suggests either nonequilibrium local PSO_2/PO_2 concentrations or the release of sulfur from surface deposits, since the exact PSO_2/PO_2 concentration required for the simultaneous formation of oxides and sulfides is not likely to occur in these combustion gases.

The morphology of another form of sulfidation on R7 blades is shown in figure 17. Nearly spherical chromium sulfides are seen in a nickel-rich depletion zone (~10 μ m) beneath a very thin (~3 μ m) surface oxide layer (ref. 13). This morphology closely resembles other forms of sulfidation in which the presence of molten phases can be detected. The presence of sulfidation after 400 hours but not after 200 hours may reflect a

higher metal temperature or an incubation period after which sulfidation accelerates (ref. 14). Because of the possibility of an incubation period, care must be used in interpreting the results of short-term PFB tests. While sulfidation was not severe (~20 μ m after 400 hours), sulfidation may become a serious problem after longer exposure times.

The deepest penetration of oxides and sulfides occurred at the trailing edge (fig. 18). Complex local corrosion areas extended up to 0.05 mm (2 mils) beneath the surface. Material loss from deep corrosion centers could be a major problem at thin trailing edge tips on bare blades or on severely eroded coated blades during longer tests.

Projected Life-limiting Mechanisms

On the basis of test R7 and previous rotor results, it appears that a severe form of superalloy corrosion can be initiated by the effluent of a PFB. This form may contain a liquid phase, and the onset may be related to reduced erosion rates and possibly an incubation period. Figure 19 shows the relative importance of corrosion and erosion in three of the previous tests. As solids loading (and thus erosion rate) is reduced, corrosion penetration becomes equal in importance to erosion as a source of material damage. The crossover point, that point at which they become equally important, appears to be at a solids loading of about 100 ppm (0.05 grain/std ft³) for relative gas velocities of about 300 m/sec (1000 ft/sec).

At still lower erosion rates (<0.25 mm/1000 hr; 10 mils/1000 hr), the predominant material damage mechanisms are likely to be accelerated oxidation and sulfidation, with blade temperature distribution, deposition pattern, local erosion rate, and time, determining the nature of the local attack (fig. 20). Future research should continue to focus on attempts to reduce particulate loadings and average particle size to reduce erosion. In addition, efforts should also be placed on determining corrosion-resistant coatings and materials for PFB applications in order to minimize the damage of oxide and sulfide penetration.

SUMMARY OF RESULTS AND CONCLUSIONS

As a result of a 400-hr small turbine test in the effluent of a PFB at an average temperature of 770° C (1420° F), an average relative gas velocity of 300 m/sec (1000 ft/sec), and average solids loadings of 200 ppm (0.1 grain/std ft³), the following results have been determined:

1. Improved gas cleanup with a modified two-stage cyclone separator and stabilized operations of a PFB coal combustor permitted a 400-hr turbine test in the PFB effluent. Two cyclones in series may adequately reduce solids loadings for utility turbine operations if the average particle size is small (~5 μ m).

2. Erosion of a small superalloy turbine operated in PFB effluent is still severe (1.37 mm/1000 hr; 50 mils/1000 hr) under these conditions, and the depth of corrosion attack is comparable to the average surface erosion loss.

3. Hot corrosion attack (sulfidation and accelerated oxidation) may be the major life limiting factor at low erosion rates (0.025 to 0.125 mm/1000 hr; 1 to 5 mils/1000 hr). Hot corrosion appears to be directly associated with deposits which contain sulfur-bearing species.

4. Since an incubation period may be associated with such sulfidation, long term testing is necessary to determine the resistance of both bare and coated blades to hot corrosion attack.

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TABLE I. - AVERAGE COMBUSTOR TEST PARAMETERS - 400-HR TURBINE TEST

Test period, week	Test time, hr	Combustor input flow rates				Ratio of sorbent calcium to coal sulfur	Combustor air flow rate		Combustor bed temperature				Combustor effluent solids loading		Combustor gas temperature entering separator	
		Coal		Sorbent			kg/hr	lb/hr	Bottom		Top		ppm	grain std ft ³	°C	°F
		kg/hr	lb/hr	kg/hr	lb/hr				°C	°F	°C	°F				
1st	25	13.5	30	1.8	3.9	2.0	297	661	1013	1855	935	1715	2900	1.58	888	1631
2nd	90	14.0	31	↓	4.1	2.1	292	648	1016	1861	983	1802	2338	1.25	923	1693
3rd	84	14.0	31		3.9	2.0	313	695	1007	1844	945	1733	3366	1.80	903	1657
4th	79	14.0	31		4.0	2.0	318	707	1022	1872	956	1753	4133	2.21	923	1694
5th	123	14.4	32	↓	4.0	2.0	322	716	1025	1877	1005	1842	2880	1.54	942	1728

TABLE II. - AVERAGE EFFLUENT GAS ANALYSES FROM SEPARATOR INTO TURBINE - 400-HOUR TURBINE TEST

Test period, week	Test time, hr	Separator exit gas temperature		Separator exit gas loading		Gas oxygen concentration, percent	Gas carbon dioxide content, percent	Gas nitrogen oxides content, ppm	Gas sulfur dioxide content, ppm	Gas carbon monoxide content, ppm	Gas hydrocarbon content, ppm
		°C	°F	ppm	grain						
					std ft ³						
1st	25	811	1492	1221	0.653	11.8	6.6	242	---	11	7
2nd	90	882	1619	151	.081	12.6	7.6	266	231	16	↓
3rd	84	861	1582	151	.081	13.0	7.3	242	288	10	
4th	79	822	1510	99	.053	12.2	7.3	248	306	11	
5th	123	923	1657	66	.032	8.4	5.0	209	292	3	↓

TABLE III. - CHEMICAL AND X-RAY ANALYSES OF COMPOSITION OF SELECTED FUEL, SORBENT, AND SOLIDS SAMPLES

Constituent	PFB solids				Fuel and sorbent	
	Separated by cyclone		Through turbine		Coal ash from Pittsburgh No. 8 coal (total, 7.94%)	Grove City limestone
	Chemical analysis	X-Ray analysis	Chemical analysis	X-Ray analysis		
Average content, wt%					wt% of ash	wt%
Silica	36	6	28	7	47	1.2
Alumina	18	-	16	--	25	.25
Ferric oxide	13	6	14	5	17	.11
Calcium sulfate	^a 9	7	^a 26	12	---	---
Calcium oxide	^b 15	-	^b 3	--	4	^c 53
Magnesia	1	-	1	--	1	.30
					wt% of coal	
Sulfur	2.2	-	6.0	--	1.9	.08
Sodium oxide	.026	-	.119	--	---	---
Potassium oxide	.088	-	.175	--	---	---

^aCalculated from total sulfur content.^bAdjusted for calculated CaSO₄ value.^c97% CaCO₃.

TABLE IV. - AVERAGE IBT TEST CONDITIONS

Test	Material	Coal	Sorbent	Solids loading			Test time, hr	Inlet gas temperature,		Relative gas velocity,	
				ppm	grain std ft ³	percent <20 μ m		°C	°F	m/sec	ft/sec
R3	Alloy 713LL	Pittsburgh No. 8	Limestone	560	0.3	73	164	690	1270	260	850
R4	IN-792 + Hf ↓	Ohio	Dolomite	2800	1.5	55	13	780	1440	330	1100
R5		Ohio	Limestone	2600	1.4	79	12	780	1440	330	1100
R6		Pittsburgh No. 8	Limestone	750	.4	--	29	770	1420	330	1100
R7		Pittsburgh No. 8	Limestone	180	.1	72	400	770	1420	300	960
R7-A	IN-792 + Hf	Pittsburgh No. 8	Limestone	370	0.2	--	0-194	770	1410	270	890
R7-B	IN-792 + Hf	Pittsburgh No. 8	Limestone	75	.04	--	194-400	780	1430	310	1020

TABLE V. - IBT EROSION/CORROSION RESULTS

Test	High temperature	High velocity	High solids loading	Erosion rate, ^a		Erosion to bare metal, percent of surface area	Maximum corrosion depth, μ m
				mm 100 hr	mils 100 hr		
R3				0.1	40	40	5 - 10
R4	X	X	X	^b 3.3	^b 1300	90	↓ 10 - 20
R5	X	X	X	^c 1.4	^c 570	50	
R6	X	X		.6	230	50	
R7	X	X		.02	7	10	

^aProjected for full admission.^bDolomite sorbent.^cLimestone sorbent.

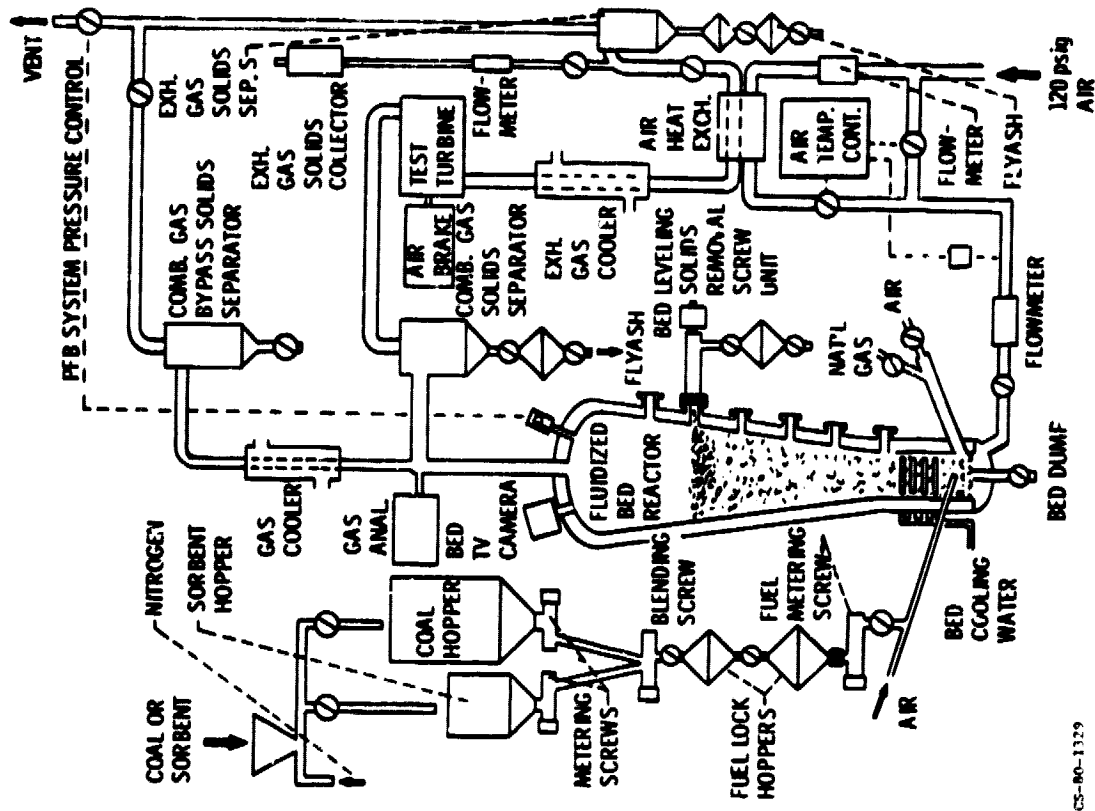


Figure 2 - Schematic of combustion and turbine test systems.

CS-NO-1129

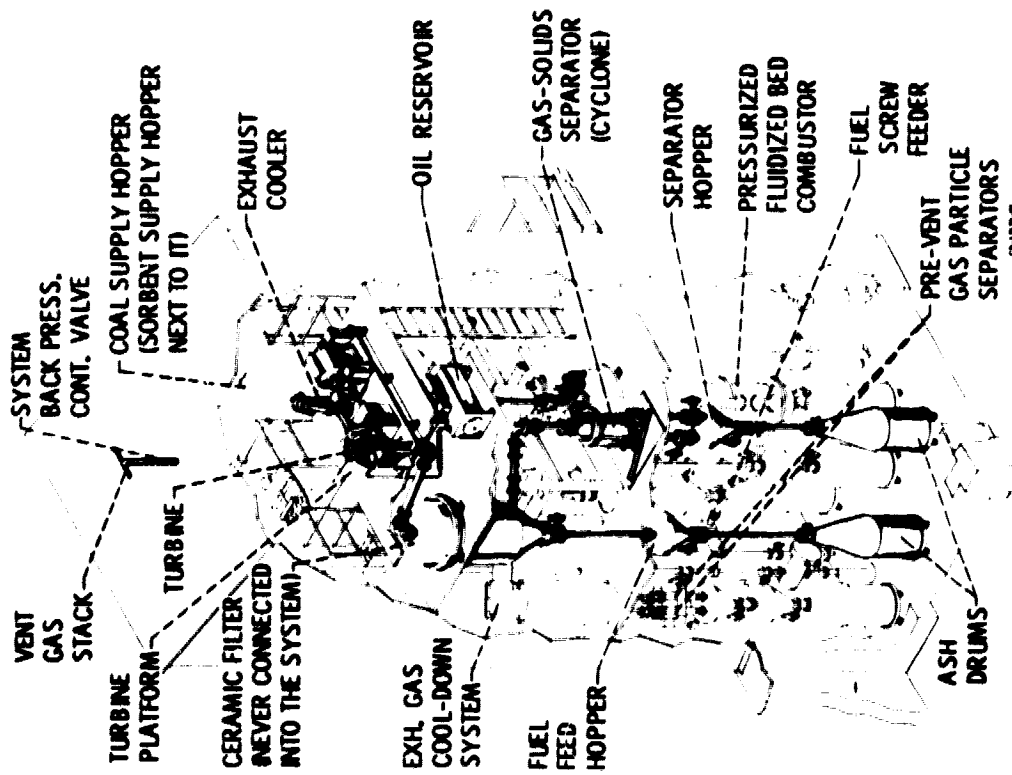


Figure 1 - Lewis PFB test cell.

CS-1129-2



LEADING EDGE



TRAILING EDGE

Figure 14. - IN-792 IBT - sulfide and oxide penetration of R7-B blade after 400 hr at 780° C (1430° F) and at 370 ppm (0.2 grain/std ft³) for first 200 hr and 75 ppm (0.04 grain/std ft³) for last 200 hr.

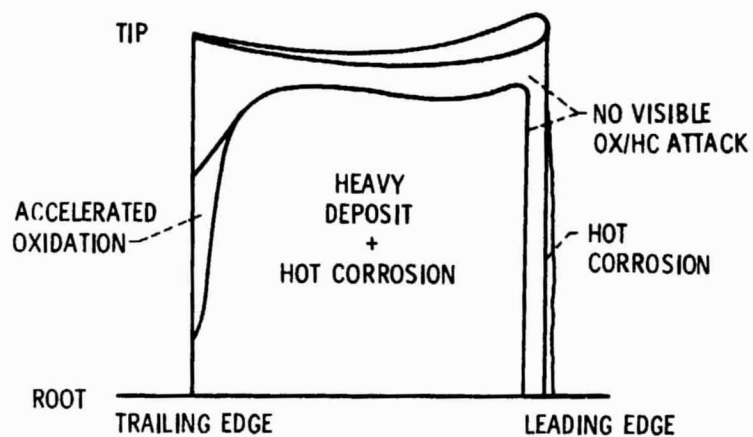


Figure 15. - Suction-side erosion and corrosion of R7-B blades after 400-hr test. CS-80-1678

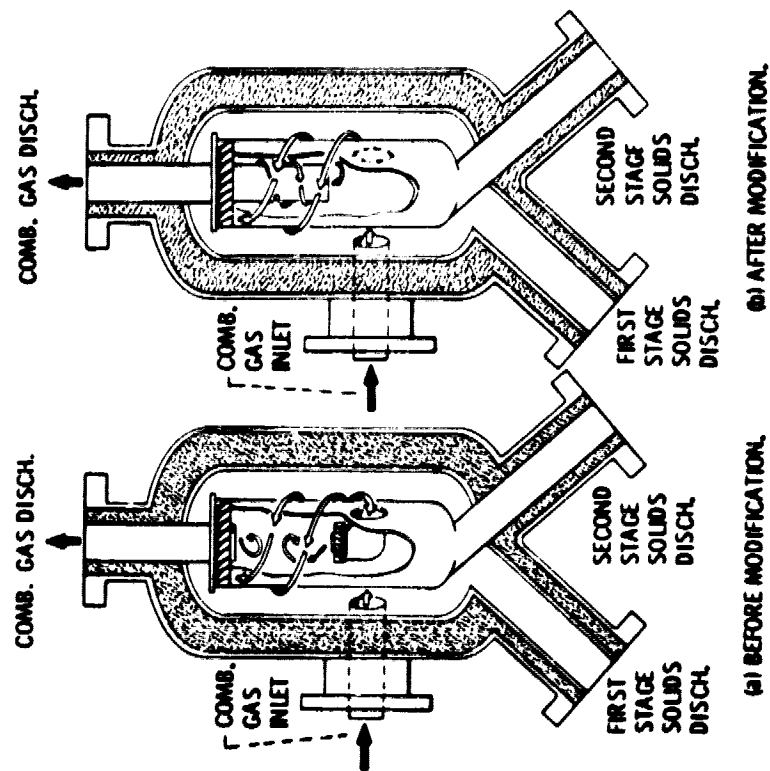


Figure 3. - Cyclone gas solids separator.

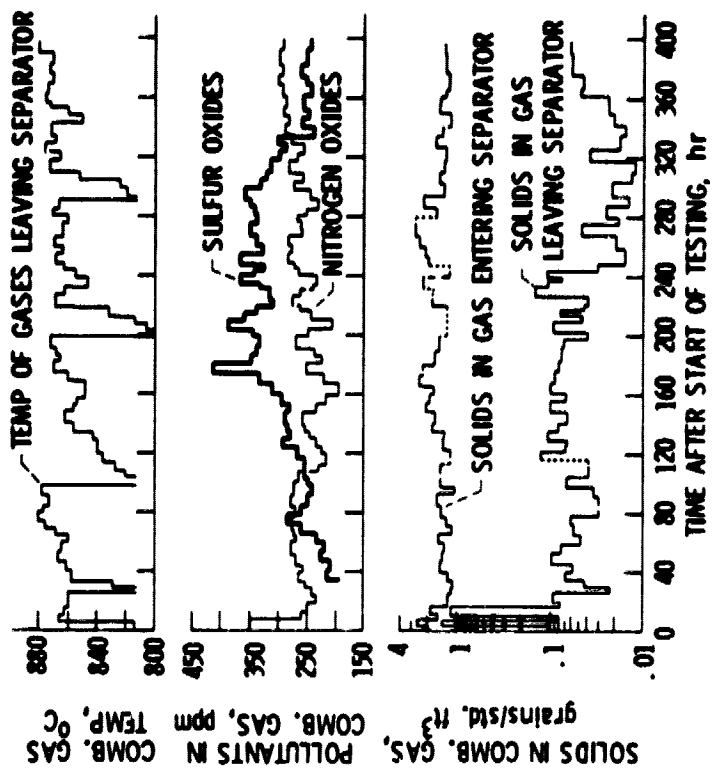
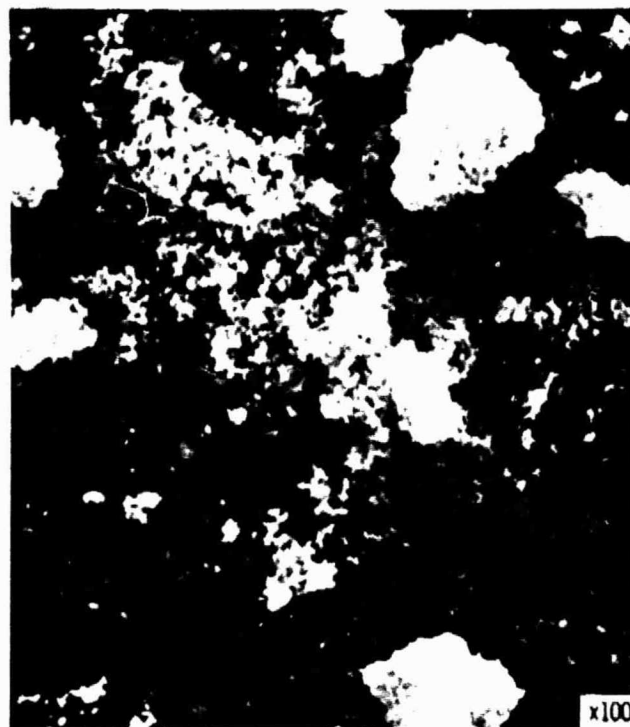
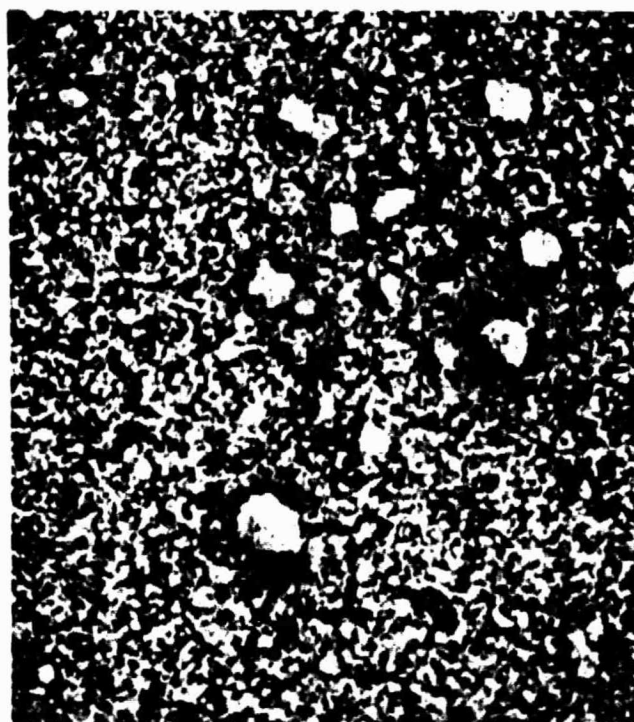


Figure 4. - Variation in gas temperature and pollutants with time.

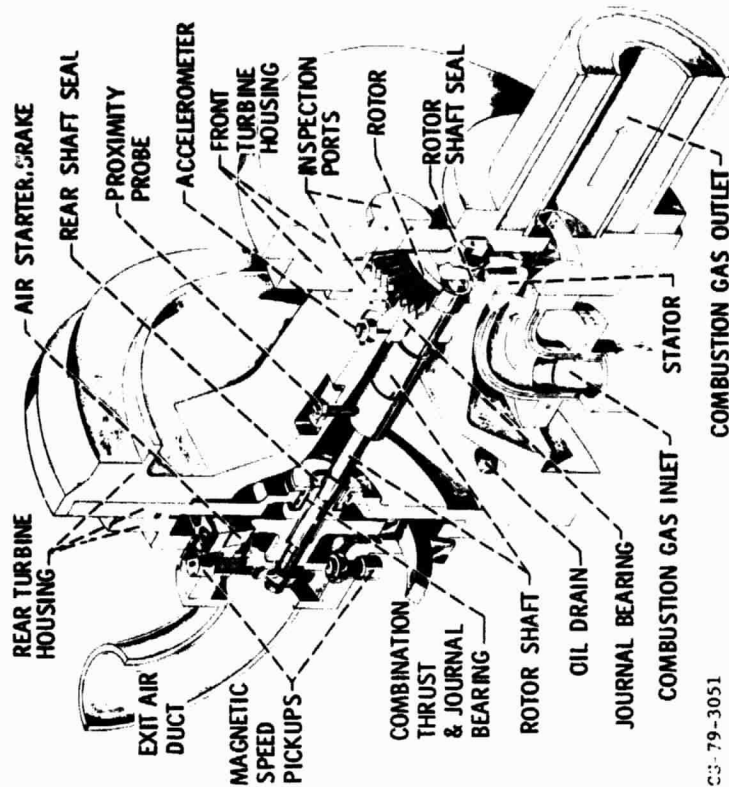


(a) DRY SIEVED FRACTION GREATER THAN 100 μm IN SIZE.



(b) SIEVED FRACTION LESS THAN 100 μm IN SIZE.

Figure 5. - Particles through turbine.



CS-79-3051

Figure 7. - Isometric section al drawing of turbine.

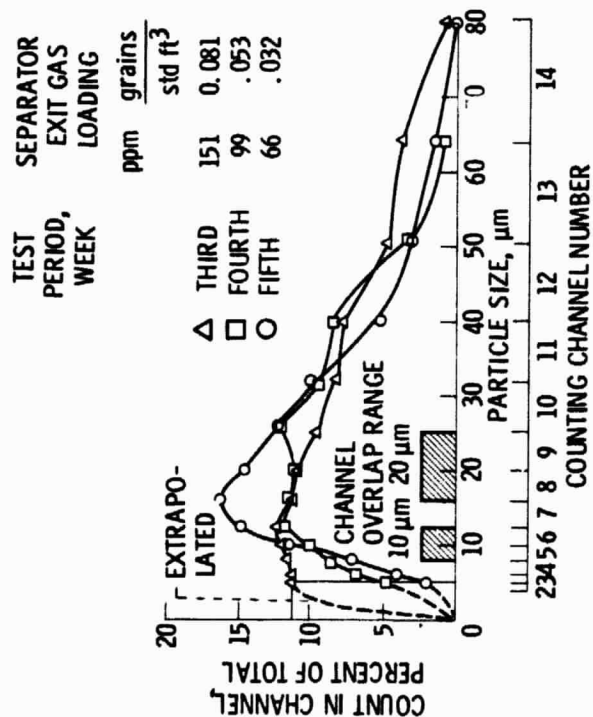


Figure 6. - Particle size distribution by Coulter analysis. (Solute: 80 percent ethanol, 15 percent glycerin, and 5 percent LiCl by weight.)

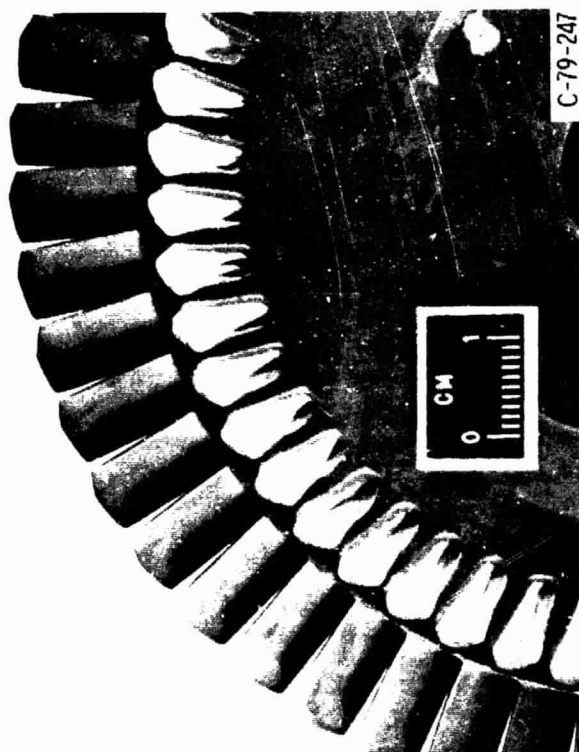


Figure 8. - Erosion of R5 rotor blade tips after 12 hr at 780° C (1440° F) and 2600 ppm (1.4 grains/std ft³).

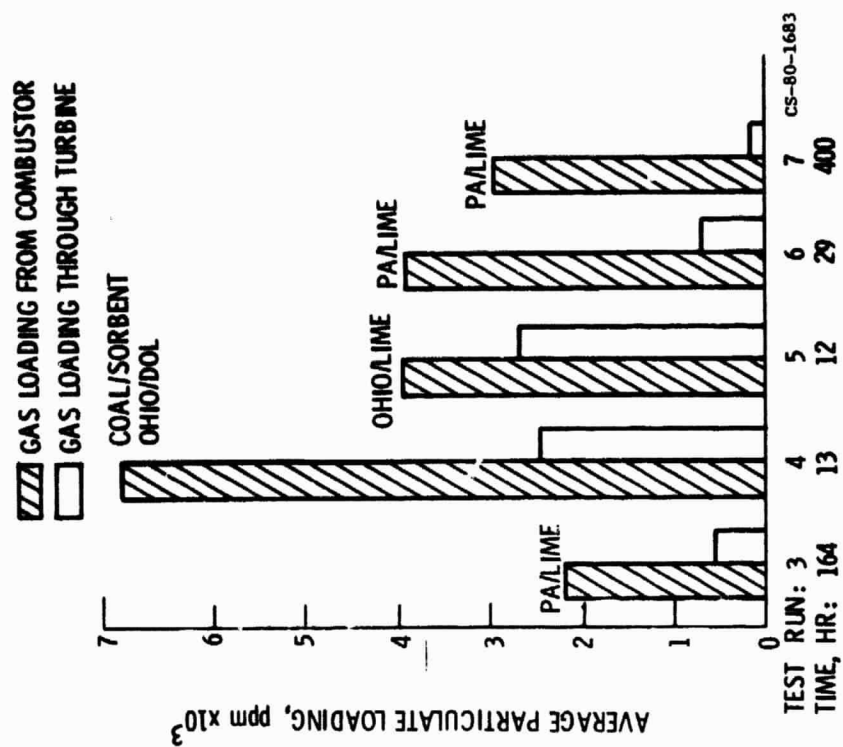
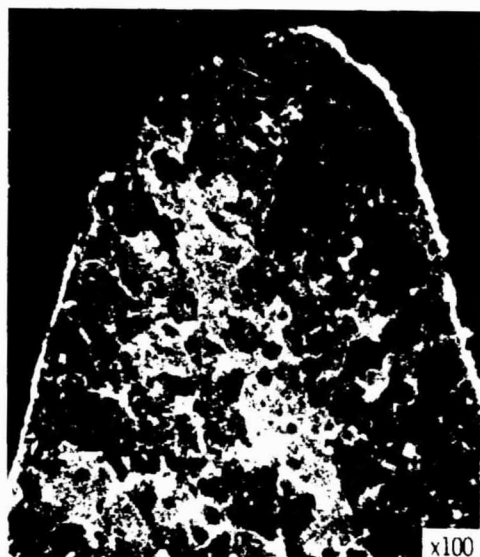


Figure 9. - Combustion gas solids cleanup.



LEADING EDGE



TRAILING EDGE

Figure 10. - IN-792 1BT - oxide penetration of R7-A blades after 200 hr at 780° C (1430° F) and 370 ppm (0.2 grain/std ft³).



SURFACE Al, Ti
OXIDES

SUBSURFACE
ALUMINUM
OXIDE

ALUMINUM
DEPLETION
ZONE

SUBSTRATE

CS-80-1691

Figure 11. - IN-792 + Hf - accelerated oxidation of R7-A blades after 200 hr at 780° C (1430° F) and 370 ppm (0.2 grain/std ft³).

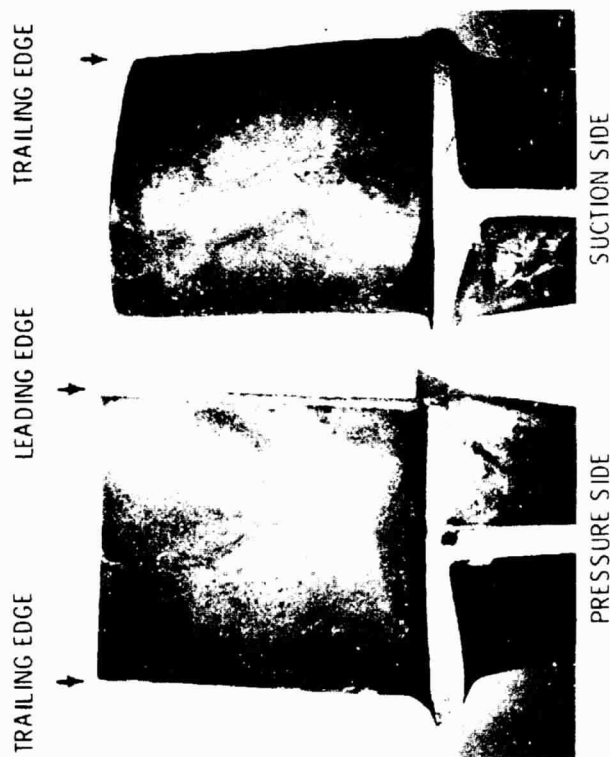


Figure 12. - Surface appearance of R7 rotor after 400 hr at 780° C
 1430° F and 180 ppm (0.1 grain/std ft³).

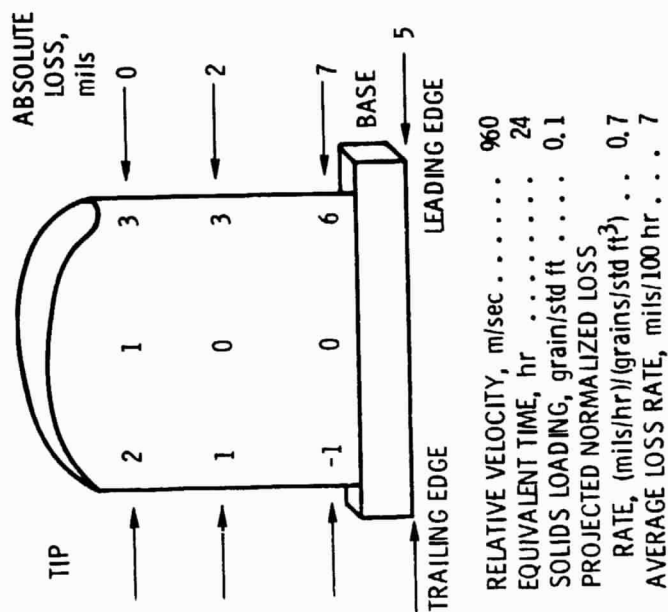
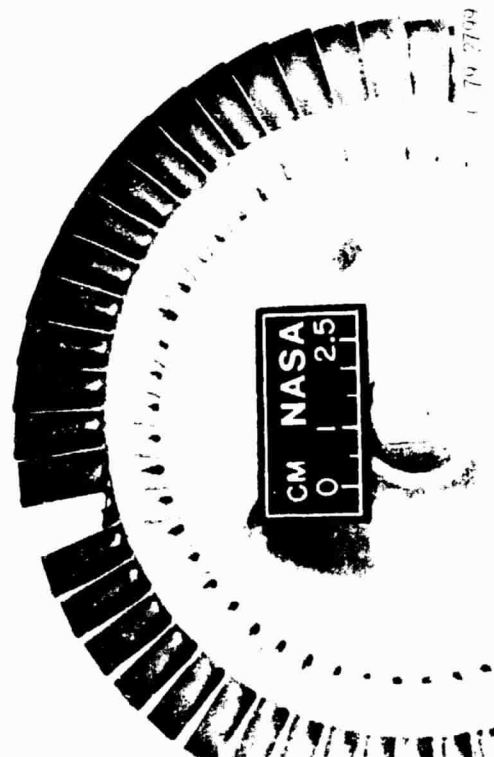
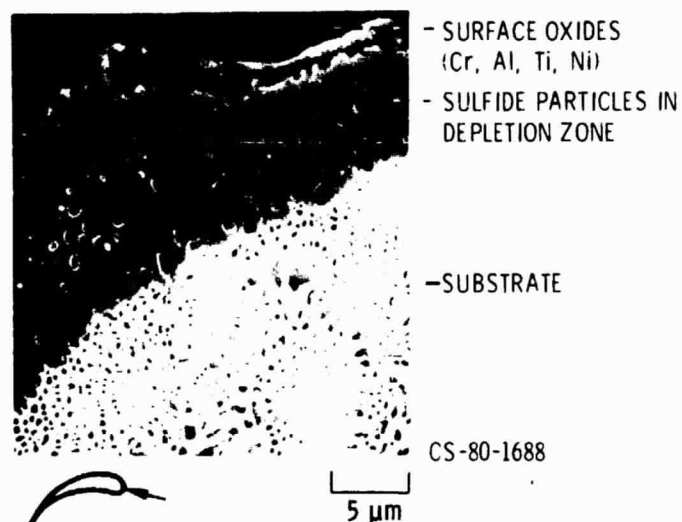


Figure 13. - IN-792 + Hf IBT - erosion loss of R7-B blades after 400 hr. Projected for full admission.

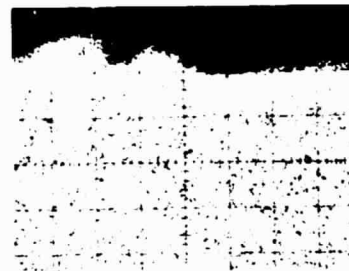




ELECTRON MICROPROBE ANALYSIS



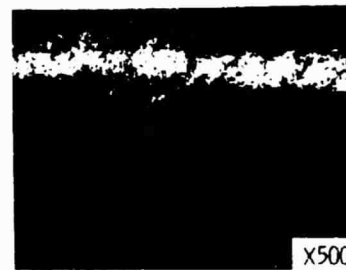
SECONDARY ELECTRON IMAGE



NICKEL



CHROMIUM



SULFUR CS-80-1684

Figure 17. - IN-792 + Hf JBT - sulfidation of R7-B blades after 400 hr at 780° C (1430° F) and at 370 ppm (0.2 grain/std ft³) for first 200 hr and 75 ppm (0.04 grain/std ft³) for last 200 hr.

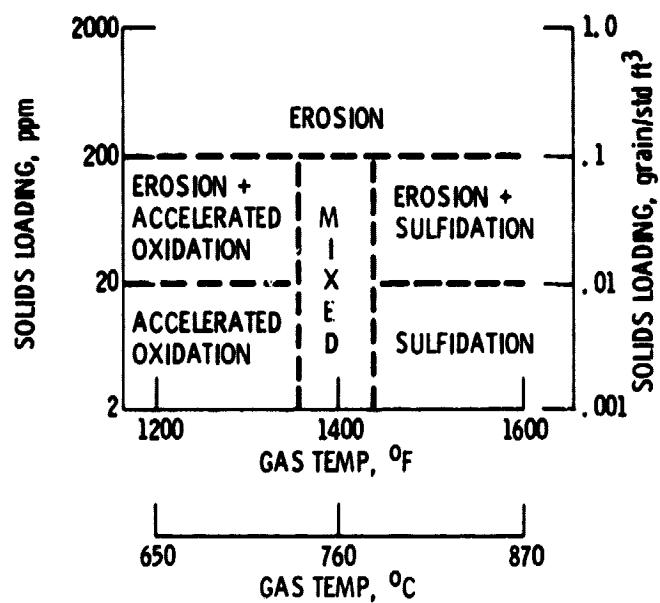


Figure 20. - PFB turbine projected life-limiting mechanisms. Gas velocity, 300 m/sec (1000 ft/sec).

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16. Abstract <p>A pressurized fluidized bed (PFB) coal-burning reactor was used to provide hot effluent gases for operation of a small gas turbine. Preliminary tests were run to determine the optimum operating conditions that would result in minimum bed particle carryover in the combustion gases. Factors that affected carryover were type of coal burned, bed dimensions, combustion air distribution to the bed, heat losses in the bed, and bed temperature. Solids were removed from the gases before they could be transported into the test turbine by use of a modified two-stage cyclone separator. Design changes and refined operation procedures resulted in a significant decrease in particle carryover, from 2800 to 93 ppm (1.5 to 0.05 grains/std ft³), with minimal drop in gas temperature and pressure. The SO_x and NO_x pollutants in the gas were below Federal limits. The achievement of stable burn conditions and low solids loadings made possible a 400-hr test of a small superalloy rotor, 15 cm (6 in.) in diameter, operating in the effluent. Average gas temperature was about 770° C (1420° F) at 6 atm pressure, and the absolute gas velocity at the rotor inlet was about 460 m/sec (1500 ft/sec). Blades removed and examined metallographically after 200 hr exhibited accelerated oxidation over most of the blade surface, with subsurface alumina penetration to 20 μm. After 400 hours, average erosion loss was about 25 μm (1 mil). Sulfide particles, indicating hot corrosion, were present in depletion zones, and their presence corresponded in general to the areas of adherent solids deposit. At these solids loadings, sulfidation appears to be a materials problem equal in importance to erosion.</p>			
17. Key Words (Suggested by Author(s)) Gas turbine; Corrosion; Pressurized fluidized bed; Coal combustion; Superalloys; Oxidation; Sulfidation		18. Distribution Statement Unclassified - unlimited STAR Category 26	
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